DOCUMENT RESUME

ED 374 011 SE 054 946

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TITLE Conceptual Development: Re-examining Knowledge Construction in Science.
PUB DATE Apr 94
NOTE 30p.; A paper presented at the Annual Meeting of the American Educational Research Association (New Orleans, LA, April 5-8, 1994).
PUB TYPE Reports - Research/Technical (143) -- Speeches/Conference Papers (150)

EDRS PRICE MF01/PC02 Plus Postage.
DESCRIPTORS *Concept Formation; *Constructivism (Learning); Criticism; Educational Research; *Electricity; Elementary Education; *Misconceptions; *Science Education; Science Projects
IDENTIFIERS *Conceptual Change

ABSTRACT

A study involving upper elementary school students (n=30) was conducted to examine conceptual change and constructivism. It is argued that a constructivist view of learning is antithetical to a vision of conceptual change in which teachers act in a diagnostic and remediate manner to help students rid themselves of their inaccurate ideas. It further asserts that this vision, which has been premised on the results of studies which depict students' ideas as highly resistant to change and interfering with the construction of accepted scientific knowledge, stems from methodologically flawed work from a constructivist perspective. This study presents the methodology and findings used to refute the notion that students' ideas are highly resistant to change. Also discussed are the implications of the results with respect to: (1) characterizing knowledge construction; and (2) conducting research on student learning within a constructivist framework. (ZWH)

Conceptual Development:
Re-examining Knowledge Construction in Science

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April 1994

Paper presented at the Annual Meeting of *American Educational Research Association*, New Orleans, LA.

Introduction

In the last two decades there has been an enormous amount of research documenting that, in many topic areas, students have knowledge about the natural world that is substantially different from that of scientists. This knowledge is developed initially as a consequence of interactions with the physical world in everyday life; hence, students often enter instruction in science with ideas that are contradictory to the content goals of the instruction. Such work has led to a substantial body of research focused on changing those conceptions into ones that are compatible with accepted scientific knowledge – a process commonly referred to as conceptual change – and the implementation and assessment of instructional strategies to facilitate conceptual change. Some successes have been reported, but the prevailing view is that conceptual change is difficult to achieve, even in response to science instruction intended to promote it (Chin & Brewer, 1993; Confrey, 1990; Driver & Easley, 1978; Hewson & Hewson, 1983; Osborne & Freyberg, 1985).

Recently, researchers have begun to reevaluate and reexamine the conclusions of this body of research, and the characterizations of the knowledge-building process that it spawned. Smith, diSessa, and Roschelle (1993) argue that the basic premise of constructivism, that students build knowledge using their existing knowledge, is incompatible with conceptual change notions that the appropriate instructional approach is to have students confront and replace their conceptions. We agree that a constructivist view of learning is antithetical to a vision of conceptual change in which teachers act in a "diagnose and remediate" manner to help students rid themselves of their inaccurate ideas. Furthermore, we suggest that this vision, which has been premised on the results of studies which depicted students' ideas as highly resistant to change and interfering with the construction of accepted scientific knowledge, stems from methodologically flawed work from a constructivist perspective.

Methods for evaluating student learning typically produced *static* pictures of student understanding in that they were images at a point in time. When that static picture was the same after instruction (whether or not the instruction was assessed to determine whether it was conducted in a constructivist manner) it was simple to conclude that students' *lay conceptions*[1] impeded their learning, rather than to consider other reasons for the result. We argue that *static* images of student learning are ill-suited to making claims about the construction of knowledge, and thus is ill-suited to make claims about learning science from a constructivist viewpoint. In contrast, our work with upper elementary school children examines student thinking in *dynamic* ways. We are focusing on the topic area of electricity, and we present students with manipulable situations (actual electric circuits) in which they make predictions, and then test them out or simply try things to gain more information with which to derive possible explanations. We contend that this dynamic situation is consistent with capturing knowledge construction from a constructivist viewpoint, and necessary to make claims about the process of constructing knowledge.

In this paper we describe our methodological approach, and present findings which contradict the notion that students' ideas are highly resistant to change. We will describe these findings, and discuss their implications with respect to: (a) characterizing knowledge construction, and (b) conducting research on student learning within a constructivist framework.

Theoretical Framework

The development of knowledge is now generally considered to be a process in which individuals receive environmental stimuli and construct meaning and knowledge from it by connecting the new information with what they already know. Early studies in this genre began, perhaps, with Piaget, but grew beyond his work as researchers became interested in the *content-specific* ideas that students hold, and the relationship of those ideas to their subsequent knowledge construction. A substantial body of research has been built in the last 20 years, documenting students' specific ideas on topics within the physical, earth, and life science disciplines that are commonly taught in schools and colleges. A number of those studies focused on designing and carrying out instruction to promote a change in conceptions because many students were found to have ideas that are inconsistent with accepted scientific knowledge (see reviews such as Confrey, 1990; Driver & Easley, 1978; Driver, Guesne, & Tiberghien, 1985;

Gilbert & Watts, 1983, Hewson & Hewson, 1983). For explanatory purposes, we shall refer to this broad body of research as the conceptual change literature.

General conclusions from the conceptual change literature were that students' ideas are highly resistant to change and interfere with instruction (e.g., Cohen, Eylon, & Ganiel, 1983; Eaton, Anderson & Smith, 1984; McCloskey, 1983; Wiser, 1986), and that they persist despite instruction designed to help students change their conceptions (Hewson & Hewson, 1983; Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993; Roth & Anderson, 1988; Zeitsman & Hewson, 1986). Some early criticisms were leveled at these conclusions, and they have recently begun to increase. There are criticisms both on methodological/analytical and empirical grounds as well as on epistemological grounds.

Methodological/analytical criticisms include the following. First, some researchers have questioned claims that student knowledge is coherent and theory-like (e.g., diSessa 1988), characteristics which were used to explain why student knowledge was resistant to change. Second, Lawson (1988) has argued that the claims are over-generalized because many of the studies indicating resistance to change have been conducted in the physical sciences. In the cited work he questioned whether similar situations exist broadly with respect to the development of understanding of biological concepts. Third, some researchers have been critical of conclusions about the requirements of instruction to facilitate conceptual change. One criticism has been that the instruction or the context of instruction was not typically evaluated in studies examining instruction intended to facilitate conceptual change; hence, competing hypothesis arising from other variables in the environment have not been considered (e.g., Hashweh, 1986, 1988). Another criticism has been that instructional studies in the conceptual change literature typically ignored motivational processes that are integral to achieving conceptual change; ignoring, for example such important issues as whether students held the motivational goal of *understanding* during the learning process (Pintrich, Marks, & Boyle, 1993; Boyle, Magnusson, & Young, 1993; Strike & Posner, 1992).

Empirical criticisms include the following. First, Clement and his colleagues have questioned that all of students' knowledge is inconsistent with scientific knowledge. They have focused on identifying students' accurate knowledge and how that can be used as building blocks to scientific understanding. Their strategy in doing so has been to develop *bridging analogies* that may be used to help students link their knowledge with more abstract scientific knowledge in ways they permit themn to accurately apply that knowledge in a wide range of situations. Research investigating the utility of using those analogies to help students' construct accurate scientific understanding has shown positive results (e.g., Clement, Brown, Zietsman, 1989). Second, there is recently evidence that students can construct scientific understanding from ideas that are contrary to the desired scientific knowledge, despite the fact that the instruction was not *specifically* designed to rid the students of their inaccurate knowledge (Muthukrishna, Carnine, Grossen, & Miller, 1993).

The most serious criticisms of conclusions from the conceptual change literature have been leveled on *epistemological* grounds. Gilbert and Watts (1983) first drew attention to this in their review of research examining student science learning in which they discussed different epistemological assumptions underlying the work that they examined. The point they make is that different paradigms have guided this work, and as such, studies have been undertaken for different reasons and with different goals. To illustrate their point, they describe three different views of the notion of "concept" that are implicit (but not necessarily explicitly acknowledged) in the studies they reviewed. They argue that clearly defined philosophical orientations are necessary for conducting this type of work if we are to be successful at building knowledge about how students come to understand scientifically accepted ideas.

This point is argued even more strongly in recent work by Smith, diSessa, and Roschelle (1993) who contend that the conclusions drawn in much of the conceptual change literature that lay conceptions interfere with learning and must be eradicated is antithetical to the basic premise of constructivism that new knowledge is built from prior knowledge. They argue that there has been too much of a focus on how students' thinking and ideas are flawed with respect to scientific reasoning and knowledge, and too little attention paid to how students use their ideas to develop and improve their understanding of the physical world. Gilbert, Osborne, and Fensham (1982) made a similar point a decade ago when they argued that the understandings that students have "are, *to them*, logical and coherent [emphasis added]" and a necessary starting point for building new knowledge (p. 631).

We concur with this view, and believe that it is important to take a developmental view in examining student learning, where the focus is on how students use their ideas – whatever they may be – and develop new understanding. The context for investigating student thinking in this way is critical. In much of the research in the conceptual change literature, the contexts in which students' ideas were examined were *static*. That is, students were asked to describe or explain their thinking about scientific terms or physical *events* or *instances* that were shown or depicted. We argue that this context was partly responsible for the characterization that students' ideas are resistant to change because it was not probable that researchers would see any change when the nature of the interview context focused on static situations. Then, when similar ideas were used following instruction, it was not uncommon for the conclusion to be drawn that students' ideas interfere with instruction and are resistant to change, despite the fact that competing hypotheses were not necessarily ruled out.[2] We consider it inappropriate to draw such conclusions given the static nature of the contexts in which student understanding was investigated. Instead, we argue that *dynamic* contexts must be employed to examine student thinking for the purpose of making claims about knowledge construction. A dynamic context permits the gathering of *direct* evidence of how students construct knowledge.

We define a *dynamic* context as one in which the student can get feedback about the viability of his or her ideas in explaining physical phenomena, particulary from personally manipulating the context. For example, in our work with electricity, we present students with actual electrical (DC) circuits, and they can manipulate the circuits to see what happens. We first ask each student to predict what would happen for a particular set of conditions, and then we have them set up the conditions and describe what they observe. Finally, we ask them to explain why they think what they observed occurred.

This approach makes the interview context an instructional one because information from the environment – the circuit – is available for the students to consider in evaluating the adequacy of their ideas. Students can further evaluate their ideas by changing and manipulating the circuits in whatever way they think will provide helpful information (feedback). Whereas some may consider such a context to be inappropriate, we argue just the opposite: this approach permits more direct observation of student thinking in a way that is likely to lead to valid claims about the process of knowledge construction. In support of our claim, cognitive psychologists interested in developmental issues are advocating an approach called the microgenetic method (Siegler and Crowley, 1991), which has some features that are similar to our approach. The microgenetic method is particularly suited to studying change (which in their case is cognitive development and in our case it is conceptual development), and it is described as being a particularly appropriate method because it "permits the subject [sic] to have the opportunity for repeated learning experiences in order to activate his [sic] existing schemes and to increase the opportunity for interaction between these schemes and the emergent schemes which result from interaction with the problem environment (Indelder et al., 1976, p. 58, cited in Siegler & Crowley, 1991). Thus, we believe our thinking is consistent with others considering similar issues.

Another feature of our approach is that it illustrates what is possible to achieve in an instructional context that is advocated in science education: inquiry-based instruction. Our requirement that the situation is manipulable, and that the investigator (the student) utilizes information from what is observed as a result of the manipulations to build understanding about the natural world, is consistent with the intent of inquiry-based instructional approaches. In that sense, our interviews mirror the kinds of experiences students are expected to have as a result of inquiry-based instruction, and it is possible for us to directly observe the type of thinking of which students are capable in an inquiry-based instructional situation. As a result, we can provide evidence with respect to the question of whether and to what extent students invent new ideas or persist in using their old ideas in the fact of contradictory evidence.

We have used the approach just described in our research with upper elementary school students. In this case, our interest in investigating their thinking and development of knowledge about electrical circuits, in particular their ideas about current flow, was fortuitous because it is easy to create manipulable situations with electrical circuits. Although there have been a number of studies of student learning with respect to electricity (e.g., Cohen, Eylon, & Ganiel, 1983; Dupin & Johsua, 1987; Fredette & Clement, 1981; Johnson & Mughol, 1978; Osborne, 1983; Psillos, Koumaras, & Valasiades, 1987; Russell, 1980; Shipstone, 1984), our work is considerably different because of our methodology. We were interested in examining the conceptual ideas that students used in reasoning about the behavior of electricity in electrical circuits, as well as examining their process of reasoning, e.g., did they change their ideas when faced with empirical evidence that contradicted their prediction.

Previous studies dealing with student thinking about electricity that are most relevant to our work are those by Osborne (1983)[3], and Russell (1980) because of the ages of the students they studied (Osborne - 8-12 year-olds; Russell - 7-14 year-olds) and because they conducted *interviews* to study students' thinking[4]. In the work by Osborne, five models of current flow were identified as characteristic of children's thinking, and they are illustrated in Figure 1. Notice that they can be broadly categorized into two types – unidirectional and bi-directional – on the basis of whether current is conceived as flowing "out" of one or both ends of the battery. Within the unidirectional category, there are two types of flow depending upon whether there is a complete path connecting both poles of the battery. The unipolar model is unique among the unidirectional models in that it does not require a complete path of electricity.

Russell (1980) reported similar results to those of Osborne with respect to the types of models employed by the students. In addition, he particularly discussed the impact of perceptual miscues on the ideas that were ventured by children about the flow of electricity.[5] What he and Osborne failed to explore were children's ideas about parallel circuits. Thus, not only is research needed to explore children's thinking during more interactive tasks, research is needed to examine children's thinking about parallel circuits. Our work was designed to address these weaknesses in the research literature, and is described below.

Methodology

Participants

We have been working at two sites in small cities in the midwest where instruction about electricity has occurred in six upper elementary school classrooms (third through the fifth grades). The instructional unit was inquiry-based and organized in a project format in which students became involved in the design and construction of scale models of buildings, and the design and construction of circuits to light them. Student participants in the research (n=30) were selected in consultation with their teachers to ensure data from a range of individuals in each class, taking into account socioeconomic status, gender, ability, and ethnicity.

Data Collection

Semi-structured interviews were utilized to investigate students' conceptual understanding in this study. Interviews were conducted individually and in private, following the instructional unit. That is, they contained a set of core questions, but interviewers were free to pursue unique lines of inquiry when needed to establish a participant's knowledge about the concepts of interest. In particular, given that students were permitted to manipulate the electrical circuits with which they were presented, questions sometimes varied greatly from interview to interview, depending upon the student's actions. All interviews were conducted by the authors of this paper; individuals who are experienced in interviews of this type.

The interviews consisted of presenting students with actual electrical circuits and asking them to predict and explain the behavior of those circuits; behavior that was observable such as whether a lightbulb was lit, and how bright it was; as well as behavior that was not directly observable – the flow of electricity in a circuit. The determination of circuits to use in the interview was made on the basis of the following criteria: (a) they presented challenging yet accessible situations for upper elementary school students to discuss, and (b) they duplicated circuits designed by students in their projects that illustrated possible reasoning errors with respect to the behavior of electricity. Seven circuits were used in this study, and they are shown in Figure 2. Circuits 1 and 7 represent electrical circuits that we thought would be interesting and challenging for the students with respect to discussing electricity. Circuits 2 - 6 represent variations on circuits that were designed by students in completing their project on wiring structures.

Circuits were initially presented to the students with wires disconnected from the batteries, and with all switches closed. They were shown one circuit at a time and first asked for their predictions about what they would they see when the wires were properly connected to the batteries. Students were then asked to give some justification for these predictions. After providing a prediction with some rationale, the students were then allowed to determine the accuracy of their prediction by manipulating the circuit accordingly. Whether their prediction was correct or not, students were prompted to explain why they thought the phenomenon that they observed had occurred. When the result was unexpected (to the student), students were allowed to further work with and even make changes on the circuit board to try out their ideas (as long as the circuit could be restored to its original condition). In cases in which students were trying out new ideas, the interviewer prompted them to explain *how* what they were doing helped to inform their thinking, and then*what* their manipulation of or change in the circuit told them.

Several questions about each circuit were posed to the students. One concerned whether the lightbulbs would light, and if so, how would they explain that. Another was how bright the lightbulbs would be, in comparison to one another, and (sometimes) in comparison to lights in other circuits. Students were expected to provide justification for their responses. Finally, students were asked how they envisioned the flow of electricity in the circuit. Once students saw the results and were able to provide an explanation for them, they were asked what they might do to the circuit to test their explanation.[6]

Interviews were audio-taped, and the interviewer kept detailed notes on circuit diagrams of the circuits to record information about what the student was saying that was not readily interpretable from their words alone.

Data Analysis

Interview transcripts were analyzed using the following approach. First, a data reduction phase was employed using a form of propositional analysis similar to that employed by Pines (1977, described in Posner & Gertzog, 1982) in which participants' statements describing and explaining their thinking about each circuit was compiled. This first-level, *circuit* summary was conducted separately with respect to each circuit. Second, the major conceptual ideas exhibited by each student to explain the results in *each* circuit were identified from the summaries. This second-level *conceptual* summary helped to highlight the kinds of concepts students employed in describing and explaining electrical phenomena.

The conceptual summaries and the field notes from the interviews were then used to draw conclusions about the types of models employed by students to describe the flow of electricity in each circuit. Following that, we evaluated participants reasoning with respect to consistency in the use of models to describe the flow of electricity across the circuits.

In addition, we selected eight students for closer analysis, and constructed profiles describing patterns in the conceptual understanding and reasoning exhibited by each student. Our selection was a representative sample made on the basis of the following considerations: status variables such as grade level, gender and ethnicity, differences in types of conceptual ideas emplyed to discuss electrical phenomena, and differences in consistency in reasoning about electricity.

The profiles were developed in the following way. Frist, to construct the conceptual understanding portion of a profile, we checked the conceptual summaries of each circuit for themes in the types of ideas utilized by students to explain what they observed about the circuits. If students were not consistent in using similar ideas for the different circuits, we simply identified the range of ideas that they employed. To construct the reasoning portion of a profile, we used a conceptual framework describing the norms of scientific reasoning with respect to theory development (Smith, diSessa, Roschelle, 1993). Those norms are consistency, coherence, and completeness (p. 138). Again, the conceptual summaries for each circuit were examined with respect to evidence of these characteristics. The profiles describe each student's conceptual understanding and reasoning in general terms, with examples from each interview illustrating their understanding and reasoning.

Results

Models Of Current Flow

Analysis of the types of models used by students to describe the flow of electricity in simple circuits resulted in identifying new models not previously reported. Models previously reported were shown in Figure 1. Figure 3 shows the additional models that we identified. These models are primarily a result of asking students about the flow of electricity in parallel circuits, and indicates that the range of models identified previously were largely a function of the type of circuit used to investigate their thinking.

As with the previous set of models, the ones depicted in Figure 3 could be grouped into unidirectional or bi-directional models. In the bi-directional model group, there are two models, the Bouncing Bi-directional Model and the Crossing Currents Model. In both cases, electric current "flows" out of each end of the battery at the same time. In the Crossing Currents Model, the currents follow the wires from each end of the battery and cross at the first lightbulb, continuing through the wires on the other side of that first bulb (with respect to where the respective currents started), following the wires and crossing again at the second bulb, and continuing until each current has followed a complete path through all of the wires. In the Bouncing Bi-directional Model, there are again two currents, one from each end of the battery, but this time they do not cross paths. Instead, the current from one end of the battery "flows" through the wire to the first bulb, then up to the second bulb but staying on the same side of the circuit, then up to the third bulb in a similar "bouncing" fashion. Once at the third bulb, the current retraces its path, "bouncing" back down to where it originated.

Although both models express students' belief that current "flows" out of both ends of the battery, the Crossing Currents Model can be considered the more conceptually advanced model. Students who employed this model exhibited the understanding that current follows a complete path from one end of the battery to the other; a concept that is not exhibited in the Bouncing Bi-directional Model. In addition, this model shows evidence of the understanding that lightbulbs light because current flows through them. In the Bouncing Bi-directional Model, it is not clear what happens with the current as it "bounces" from one light to the next.

In the unidirectional model group there are three models (see Figure 3), one of which is the scientifically acceptable model. The other two models, the Bouncing Unidirectional Model and the Serpentine Model, are interesting applications of the idea of unidirectional flow to parallel circuits. Unlike one difference between the bi-directional models, both of these models show evidence of understanding that electricity must have a complete path from one end of the battery to the other in order to flow. As a result, they are more conceptually advanced models than the bi-directional models.

The difference between the Bouncing Unidirectional Model and the Serpentine Model lies in how they depict the path of the current in relation to the lightbulb. The former model is similar to the Bouncing Bi-directional model in that it is not clear whether current flows into the lightbulb. Because of this, students employing this model do not necessarily understand that the lightbulb lights because current passes through the filament of the lightbulb. The Serpentine Model, so-named because of the snake-like movement that characterized the flow of current in this model, does clearly indicate that current passes through the lightbulb. Thus, this is a more conceptually advanced model than the Bouncing Unidirectional Model.

Students' Use of Models in Explaining the Flow of Electricity

Table 1 shows the models employed by each student to describe the flow of electricity in the seven circuits that were discussed (see Figure 2). The students are organized by grade level, and the models are grouped by model type (bi- or uni-directional.), and within each type, the models progress from least to most conceptually advanced as you look from left to right. Several patterns appear in the table.

First, most students employed multiple models in explaining the flow of current in different electrical circuits. Second, the third graders showed greater variety than the older students in the models they employed to describe the flow of electricity. Third, there were more instances of third grade students employing bi-directional types of models than for the older students. These results suggest some developmental differences in the younger students.

With respect to the type of models employed, although about half of the students exhibited bi-directional models at some point in the interview, only two students showed NO evidence of understanding that current does NOT flow out of both ends of the battery. In addition, the vast majority of the students showed evidence of understanding that current passes through the lightbulb to light by employing one or more of the following models: Crossing, Serpentine, Scientific:Series, or Scientific:Parallel. Finally, more than half of the students employed scientifically accurate models in describing the flow of electricity in parallel circuits, and that even included some of the third graders. These results indicate that although many students are not employing strictly scientific models, many of the components of understanding are present in some form. We cite these results as evidence supporting Clements contention that students have accurate knowledge upon which to build.

Consistent Use of Models

Table 2 shows these same results but purely from the perspective of students' consistency in the use of models. Given the organization of the table, there are two perspectives from which consistency can be described: specific models used, and model type used. The results indicate that there were not any discernable developmental patterns with respect to consistency in use of specific models, but there seemed to be greater consistency for the older students in the *type* of model that was employed to describe the flow of current.

Coherence in Models

These data on consistency also allow us to note some patterns with respect to coherence and completeness. First, for those students who were not judged as being consistent, it is really more accurate to say that their ideas were incoherent because they employed both unidirectional and bi-directional models. Second, a less obvious form of coherence is related to the adequacy of their model with respect to being able to account for specific behaviors in a circuit. In other words, although many students were consistent in employing ideas that current is unidirectional or bidirectional (model type column), their ideas about how that applied in cases of specific circuits were not necessarily coherent. It is not coherent, for example, to employ a scientifically acceptable model for some parallel circuits but employ a serpentine model for others as did student #2, a third grader. Similarly, it is not coherent to employ a crossing model for some parallel circuits and a two-way bouncing model for other parallel circuits as did two fifth grade students (#19, and #27). Thus, we need to look to the "model" column for information on coherence.

It is most instructive in this subtler issue of coherence to look at the cases where students were judged as consistent in the model they employed where the model was a unidirectional one. In that case, there were two possibilities of being assessed as employing a consistent model. One possibility was when a Serpentine Model was employed for parallel circuits and a scientifically acceptable model was employed for series circuits. There were four students who exhibited this pattern of reasoning: #4, #14, #21, and #25. Although these students were consistent from the perspective of the models reflecting uni-directionality and the existence of a complete path linking the poles of the battery, for the parallel circuits, the Serpentine Model limited the students in being able to account for observations when different switches in the circuit were open. Given their model, they should have predicted that when any switch is open no lights would be on. That was not the behavior of the circuit, nor was it the typical prediction of the students, and when they actually saw the results they needed to invent other ideas to account for them. Thus, they were not consistent in applying the idea reflected in the model they described, illustrating a lack of coherence, and the ideas they invented were sometimes not consistent with the model, again resulting in incoherence.

The other possibility was when scientifically acceptable models were employed for series and parallel circuits. There were eight students who exhibited this pattern of reasoning: #6, #11, #13, #16, #24, #26, #28, and #30. These students were able to be consistent in the application of the ideas in their model to all the behaviors observed in the circuit because those ideas were coherent.

General Comments About Reasoning

General themes that were noted in the analyses leading to the tables and the profiles[7] are as follows.

Consistency versus coherence across tasks. Participants generally could be categorized into one of two groups: some students exhibited the need for both coherence in their explanations within a given a circuit and to be consistent in the use of that explanation across circuits whereas other students only exhibited the need for coherence. For example, it was not uncommon for students to change their mind about the flow of electricity in a circuit presented to them late in the interview and indicate that they wanted to go back and re-explain how electricity flowed through circuits presented earlier in the interview. On the other hand, other students seemed unconcerned with contradictions in their statements across circuits. Sometimes, when prompted by an interviewer's question about the inconsistency, these students made statements that suggested each circuit worked in its own way.

Generating on–the–spot explanations. It was clear that in a number of the tasks, students were asked to generate an explanation for something they had never thought about before (e.g., the short circuit situation for Dairia). For the most part, students were generally comfortable doing this, and were not reluctant to give an explanation containing completely different ideas from what they had previously stated. This was particularly evident when students were presented with complex circuits with which they had no previous experience. For instance, when asked how electricity actually made the bulb light, one student asked, "what do you mean," indicating to us that the student had not previously considered this question. The interviewer replied by saying that the wires leadning to the bulb didn't give off light but the bulb did, prompting the student to say he thought the filament of the bulb probably had a special coating on it that the wires leading to the bulb didn't have, and that this coating gave off light when electricity passed through it. The interviewer then asked why the filament was under glass and not just a part of the wire itself, to which the student replied that it had to be under glass so the coating wouldn't rub off.

Justification of explanations. When asked to justify their predictions, on most occasions the students were able to quickly respond. In some cases, students' would modify their initial predictions as they derived an explanation. Whereas Ganiel and Eylon (1983) refer to these as "contrived" explanations because they are not based upon scientific "fact," we considered them to be an important part of constructing scientific knowledge. The kinds of explanations the students generated were varied and showed good intuition about viable possibilities for the circuit in question, and students often referred to the results of instructional activities or to personal experiences outside of the classroom as justifications for their reasoning. The accuracy of the phenomena they cited as evidence was sometimes questionable, as in the case of one student who said that switches always control the bulbs closest to them because in a house the switches control the lights for one room and not in distant parts of the house.

Willingness to change explanations. A large portion of the students were willing to change their explanation when presented with contradictory evidence as they worked with a circuit. This included changing to a qualitatively different explanation and not just a modification of their initial statements. At times this occurred when, in the process of deriving an explanation, students referred either to experiences in the classroom or with circuit boards examined earlier in their interview, and then realized that they contradicted their explanation. It was not uncommon for students who had that experience to change either their previous explanation or their new explanation to account for the new information.

Resistance to change explanations. Some students did resist changing their explanations even when confronted with contradictory evidence. In many of these situations, the students could generate no plausible alternatives so they simply retained their current thinking. In one particular instance, a student with a high level of prior knowledge about and interest in electricity when confronted with experimental evidence inconsistent with his core beliefs rejected this information out of hand, relying on experiences outside of the assessment context.

Significance

Espousing a constructivist framework is becoming commonplace in the educational literature, particularly in science education. At the same time, few have considered the implications of such a framework for integrating the large body of research done within the conceptual change paradigm. To be certain, these two views of learning are not synonymous with one another and care must be taken when crossing from one view to the other. One principle difference lies in how each paradigm views the nature of a "concept," different views of which are described by Gilbert and Watts (1983). The conceptual change paradigm generally considers concepts as the mental structures that correspond in some degree to scientific truths about the world. While there is some recognition that these structures may change or evolve, the primary focus of conceptual change research has been on overthrowing prior conceptions and replacing them with scientific conceptions, thus suggesting a rather *static* view of concepts. In a constructivist paradigm, concepts are viewed much more *dynamic*ally: a concept is something that is continuously constructed and acted upon, given the experiences of its owner. This gradual, persistent process is more akin to what has been referred to as weak restructuring of concepts (Carey, 1985; Vosniadou & Brewer, 1987). Carey suggests, as our data indicate, that such weak restructuring is far more common than the strong restructuring or overthrow of core concepts suggested by much conceptual change research.

We think that it is more useful (and accurate) to think of knowledge construction in ways reflected in Clement's work: there is much a learner brings to build scientific knowledge with, so let us focus on how we can help students develop understanding regardless of where they begin.

We argue that much is *assumed* about what we need to do to help students build scientific knowledge when they have been judged as having knowlege that is inconsistent and contrary to it. We find it useful to consider images such as Escher's painting entitled Metamorphose II (shown in Figure 4) in demonstrating that "you just don't know where you might get to from here" instead of assuming that "you can't get there from here."

Our results indicate there would be much value in continued research of this nature in which student knowledge is examined in *dynamic* situations. Perhaps then we will have much more information about the possibilities of where students' effort and creativity might lead them. One challenge will be in how to create those types of situations for different topics. Here, the role of computer technology may be very helpful. There already exist a number of simulation programs that might be very profitably used to explore student understanding (e.g., Interactive Physics).

On another front we need to ask ourselves what these results mean for instructional? In the *conceptual change* paradigm, conclusions from previous research suggest a "diagnose and remediate" instructional approach, i.e., the goal of the teacher is to "diagnose" lay conceptions (or help the students to do that), and follow with "appropriate" activities to lead the students to rid themselves of those conceptions in favor of the desired scientific understandings. In contrast, the *constructivist* paradigm values lay conceptions, and the goal of the teacher is to help students gain experience interacting with the natural world and thinking critically about how to explain what is observed. As a result, rather than promoting a view that *currently*–accepted scientific knowledge is the ultimate end-point, we argue that constructivist–based instruction should promote the view that knowledge, including scientific knowledge, continually evolves, ever-seeking to achieve more encompassing explanations. In the constructivist perspective, *how* the knowledge was constructed, and the *experiences* supporting it, *do* matter. We contend that students experiencing this type of instruction are more likely than in other approaches to develop three things: (a) cognitive skills for evaluating the adequacy of ideas, (b) syntactic knowledge relevant to scientifically testing ideas for their adequacy and explanatory power, and (c) elaborated yet *fluid* substantive knowledge of science that can readily change in the aspects that are hallmarks of scientific knowledge.

Some instructional approaches already in existence claim to be examples of constructivist orientations to science instruction (e.g., PBS); however, in the case of project-based science, there is no mention of how students' ideas will be considered, making it difficult to evaluate it with respect to the orientation toward supporting knowledge construction advocated in this paper. An approach conceived by Magnusson and being further developed in conjunction with colleagues at the University of Michigan, explicitly considers the role of students' ideas as integral to the development of understanding. This approach, called Interdisciplinary Guided Inquiry (Magnusson & Palincsar, in press), draws upon an instructional heuristic developed by Magnusson for guidance in how to plan (and conduct) instruction in ways that value the ideas and explanations generated by the students, while at the same time challenging them to evaluate the adequacy of their ideas. Further development and implementation of instruction of this type is needed to determine the possibilities for supporting students in the development of scientific understanding, regardless of their starting point. We contend that NOT starting from whereever the students are means that the students will not be able to take advantage of their own reasoning powers. By starting from their perspective and what makes sense to them, they can use the power of their own reasoning and imagination and, with our support, develop increasingly more powerful ideas; not because we told them that these are the ideas to learn, but because they were persuaded and motivated by their usefulness.

Endnotes

[1] We define lay conceptions as knowledge held by learners that differs from accepted scientific knowledge but has utility for the individual and is used for explanatory purposes. This is similar to what has been referred to as childrens' science (Osborne, Bell, & Gilbert), but our choice of terminology is intended to reflect that these conceptions are common among individuals of all ages, and differ from scientific knowledge because the norms for generating scientific knowledge are not common to the generation of knowledge for individuals in everyday life.

[2] Consider, for example, that the research did not assess whether students were really trying to understand the conceptual goals of the instruction.

[3] It is noteworthy that in Osborne's work, the students were provided additional information after their predictions, in the form of readings from an ammeter (measures current) placed at different points in the circuit. Moreover, he reports that only 5 of 37 students whose initial predictions were inaccurate were not able to change their ideas; the remaining 32 changed their ideas to conform to the new information.

[4] Many studies have been conducted using paper-pencil measures. Conclusions from these contexts may be very misleading because of difficulties students may have in interpreting the questions, particularly where circuit diagrams were used.

[5] By perceptual miscues, we mean those features of the physical layout of a circuit that suggest particular explanations which are inaccurate with respect to scientific understanding.

[6] A copy of the complete protocol can be requested from Shirley Magnusson, 1323 SEB, The University of Michigan, 610 East University Ave., Ann Arbor, MI 48109-1259.

[7] Data from the profiles are presented in Magnusson, Boyle, & Templin (1994, March).

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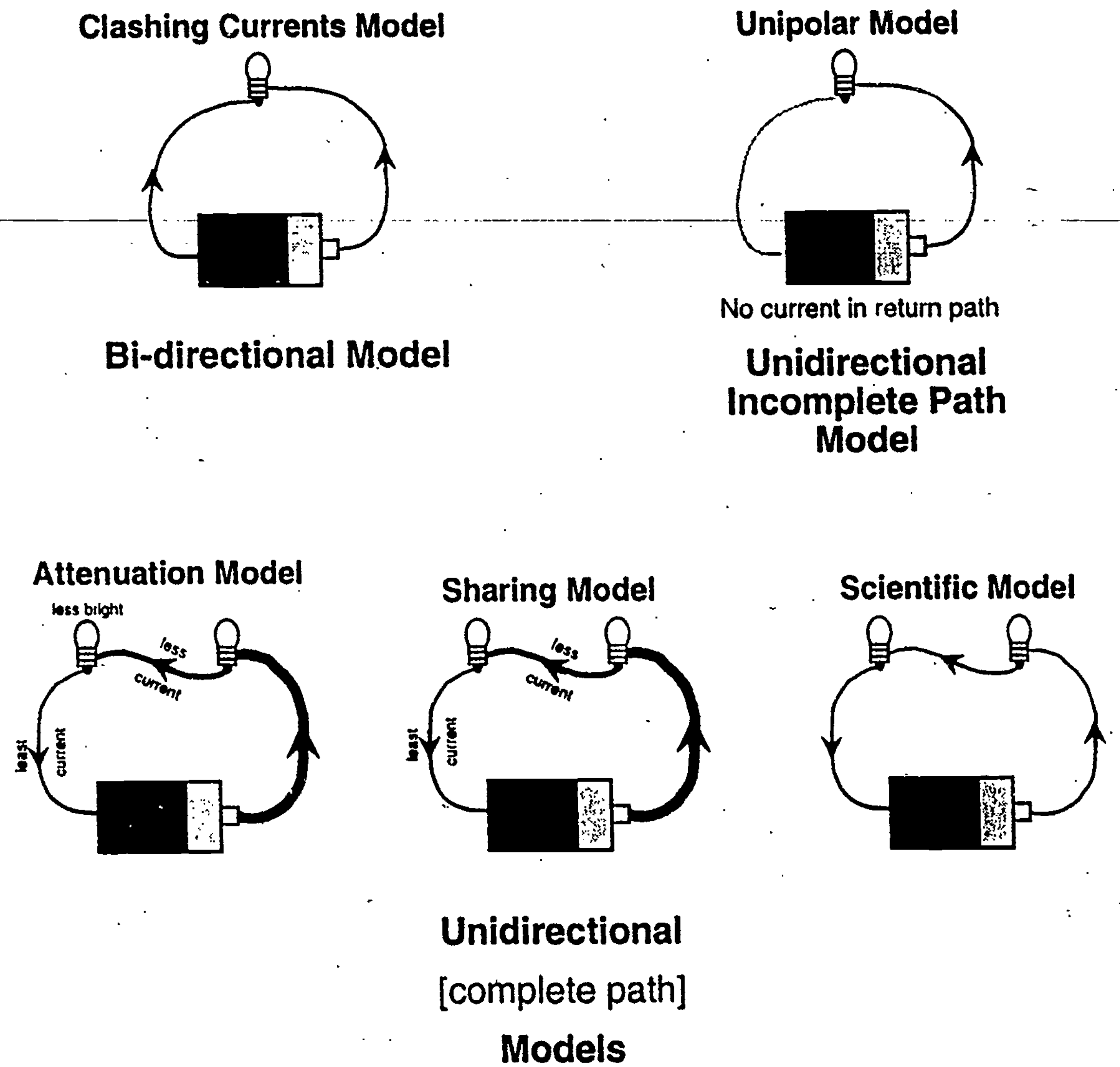

Figure 1. Students' Models of Electric Current in Simple Circuits [Adapted from Shipstone (1985) and Osborne (1983).]

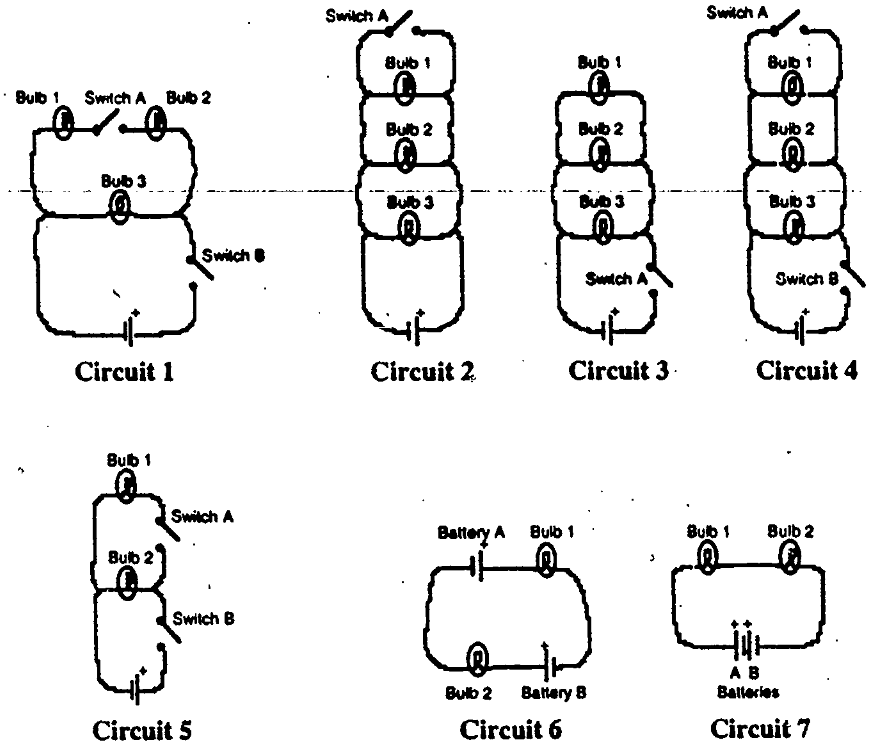

Figure 2. Circuit Diagrams of Circuits for Investigating Students' Understanding of Electricity

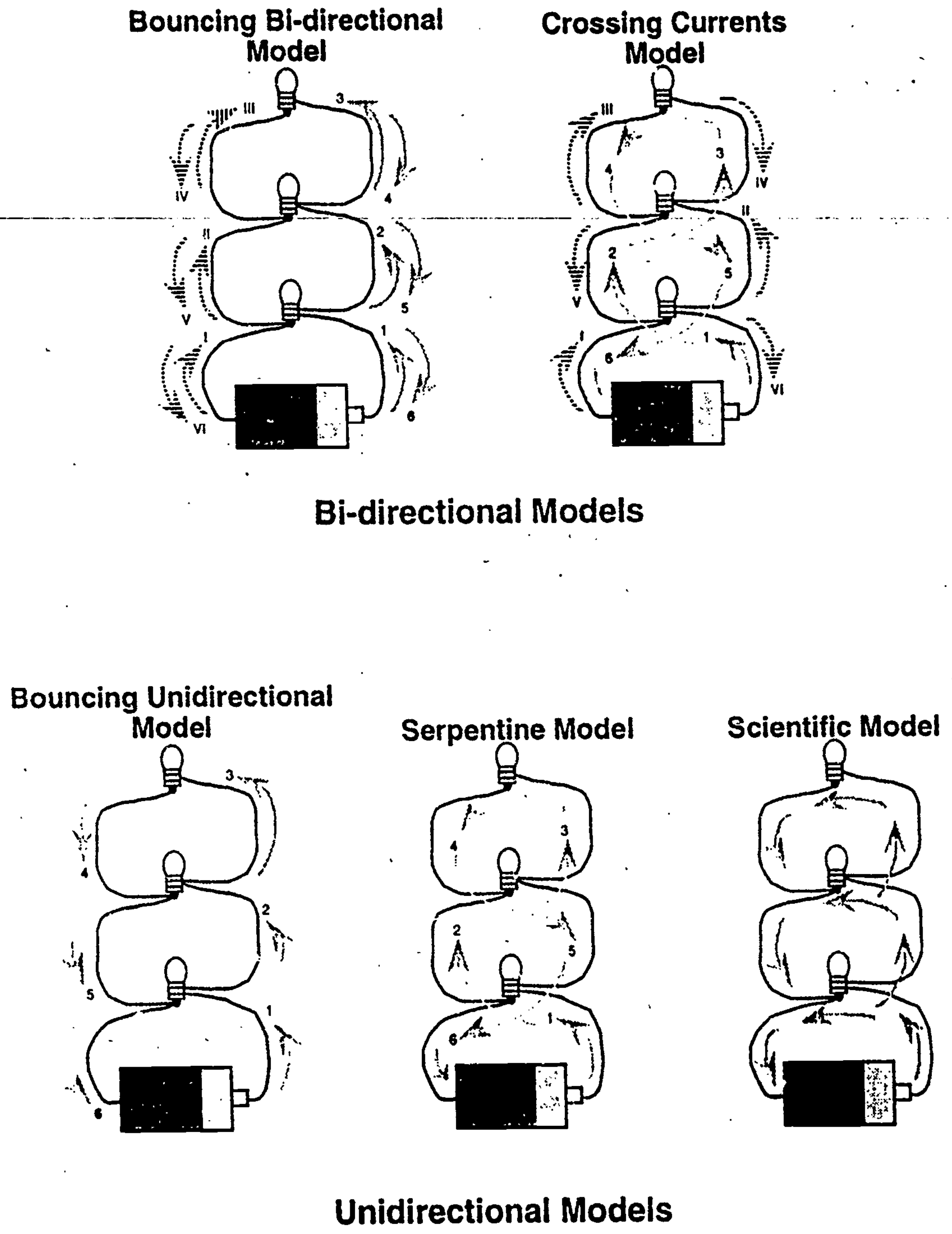

Figure 3. Additional Models Representing Students' Thinking About Electric Current

Figure 4. Metamorphose II by Escher

Table 1

Models of Electric Current Employed by Students in Describing Specific Circuits[a]

		BI-DIRECTIONAL			UNI-DIRECTIONAL				
		Lay Conceptions			Lay Conceptions			Scientific	
Grd. Lvl.	St.	Clashing	Two-way Bouncing	Crossing	Unipolar	One-way Bouncing	Serpentine	Series Circuits	Parallel Circuits
3	1		6	1?	5			7	2?, 3
	2				4		3, 5	6, 7	1
	3	2	7	1, 3				6	
	4		(2)				1, 2, 3, 4	6, 7	
	5	2, 3, 4	1, 6, 7		(4)				
	6							6, 7	1, 2, 3, 4, 5
	7		1					6, 7	2, 3, 4, 5
	8	4[b]	3, 4				1, 2, 3, 4, 5	6, 7	
	9	2, 3, 5		5				6, 7	1
4	10		4	4			1, 2, 3, 5	6, 7	
	11							6, 7	1, 2, 3, 5
	12						2	6, 7	1, 3, 5
	13							6, 7	1, 2, 3, 4, 5
	14						2, 3, 4, 5	1?, 6, 7	
5	15	1					2, 5	6, 7	3
	16							6, 7	1, 2, 3, 4, 5
	17						2, 5	6, 7	1, 3
	18			1, 2, 3, 4, 5, 6, 7					
	19		2, 3, 6, 7	1			5		
	20		2, 3, 5, 6, 7				1		
	21						1, 2, 3, 4	6, 7	
	22	1, 2, 3, 6, 7							
	23						1, 2	6, 7	5
	24							6, 7	1, 3, 5
	25						1, 2, 3, 4	6, 7	
	26							6, 7	1, 2, 3, 4, 5
	27		6	1, 2, 4, 5				7	3
	28							6, 7	1, 2, 3, 4, 5
	29					2, 3, 4		6, 7	1, 2, 5
	30					(3)		6, 7	1, 2, 3, 4, 5

KEY: ( ) Parentheses indicate a model that was replaced by another model.

[a] The numbers in the table designate specific circuits.

[b] The student only exhibited this model in describing the flow of electricity when the switch in the circuit was actually closed.

Table 2

Consistency of Students' Use Of a Specific Model of Curent Flow

Grd. Lvl.	Student	MODEL	MODEL TYPE	
3	1	-	-	
	2	-	+	U
	3	-	+/-	B
	4	+	+	U
	5	+	+	B
	6	+	+	U
	7	+/-	+/-	U
	8	-	-	
	9	-	-	
4	10	-	-	
	11	+	+	U
	12	+/-	+	U
	13	+	+	U
	14	+	+	U
5	15	-	+/-	U
	16	+	+	U
	17	-	+	U
	18	+	+	B
	19	-	+/-	B
	20	-	+/-	B
	21	+	+	U
	22	+	+	B
	23	-	+	U
	24	+	+	U
	25	+	+	U
	26	+	+	U
	27	-	-	
	28	+	+	U
	29	-	+	U
	30	+	+	U

KEY:
- + consistent
- +/- consistent with the exception of one circuit
- \- inconsistent
- B Bi-directional Flow Model
- U Uni-directional Flow Model